MEASUREMENT OF HUMAN COLOR RESPONSES USING VISUAL EVOKED POTENTIAL ELICITED BY MULTI-COLOR STIMULATION

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Abstract- **The simultaneous presentation of two color stimuli was used to determine whether a practical and rapid method of recording human color responses using visual evoked potentials (VEPs) can be done. Multi-color stimulation which consists of two iso-luminant color stimuli presented with a pseudorandom binary sequence (PRBS) were employed to elicit VEPs, and the first-order binary kernel of the VEPs was calculated using multi-input system analysis technique. The waveforms of the kernels elicited by the two color presentations were similar to those obtained by one color stimulation. This indicated that the simultaneous presentation of two color stimulation is effective in detecting color responses. However, the amplitudes of the kernels obtained by the two color stimulation method were different from those by one color stimulation. This may be because the effect of one color stimulus was weakened by the presence of the other color stimulus.**

***Keywords* - VEP, Pseudorandom Binary Sequence, Color Vision, Color Stimulation, Binary Kernel**

I. INTRODUCTION

Measurements of the responses elicited by color stimuli are important for investigating the characteristics of human color vision and for clinical testing of color vision. Because visual evoked potentials (VEPs) are objective responses to visual stimuli and can be measured noninvasively, VEPs have been used to measure and analyze the human visual system [1]-[6]. Both luminosity and chromatic response components have been found in the transient and steady-state VEPs, and analyses have indicated that VEPs can be used to test and characterize human color vision quantitatively [1]-[3].

Because the VEP has nonlinear properties, a nonlinear system identification method is useful in describing the relationship between the stimulus and the VEP [4]-[8]. Binary kernel expansion [8][9] is one of the nonlinear system identification methods and has been applied to characterize the VEP system. It has been demonstrated that the binary kernels of the VEPs include the opponent color responses, i.e., the responses of the two chromatic channels in the human visual system [4][5]. However, the VEP responses to eight color stimuli, i.e., eight individual VEP measurements, were necessary to extract the opponent color responses. Thus, it required approximately two hours to obtain the VEP recordings [4][5].

It is important and more practical if the human color responses could be recorded more quickly. Because subjects with normal color vision can perceive many colors, responses elicited by several color stimuli presented simultaneously would be necessary to measure and determine human color vision rapidly to avoid the color adaptation and/or fatigue.

In order to develop a practical and rapid method to record human color responses using the binary kernels of the VEPs, two color stimuli were presented simultaneously and its validity in extracting color-specific responses was investigated.

II. METHODOLOGY

A. Multi-input System Analysis in Binary Expansion

Causal and time invariant nonlinear systems can be described by their binary expansions [8][9] so long as the input is a binary (-1 or +1) sequence,

$$y(t)=\sum_{n=0}^{N}\sum_{\tau_n=\tau_{n-1}+1}^{R}\cdot\cdot\sum_{\tau_{n-1}=0}^{\tau_2} b_n(\tau_1,\cdot\cdot,\tau_n)x(t-\tau_1)\cdot\cdot x(t-\tau_n) \qquad (1)$$

where $x(t)$ is the input, $y(t)$ is the output, τ_n is a time delay and $b_n(\tau_1,\cdot\cdot,\tau_n)$ is the n*th*-order binary kernel. R is a memory length of the system. Identification of a nonlinear system means the identification of its binary kernels. When $x(t)$ is a pseudorandom binary sequence (PRBS or binary m-sequence), the sliced kernels of all orders are lined up along the first-order cross-correlation cycle between $x(t)$ and the corresponding system response $y(t)$ [9][10].

This principle can be expanded to a multi-input ($x_1(t), x_2(t), \ldots, x_m(t)$, *m*: number of inputs) and one output ($y(t)$) system. When a PRBS ($x_1(t)$) and its shifted PRBS ($x_2(t)=x_1(t-\sigma)$) are used as input, binary kernels for each input ($b_n^1(\tau_1,\cdot\cdot,\tau_n)$ and $b_n^2(\tau_1,\cdot\cdot,\tau_n)$, the upper indices denote the input number) that can be obtained from the first-order cross-correlation function between $x_1(t)$ and $y(t)$. This follows because PRBS are orthogonal to all of their cyclical shifts [9].

B. Color Stimulation

The stimulation and VEP measurement systems are shown in Fig. 1. The stimuli were two unpatterned colors

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Abstract

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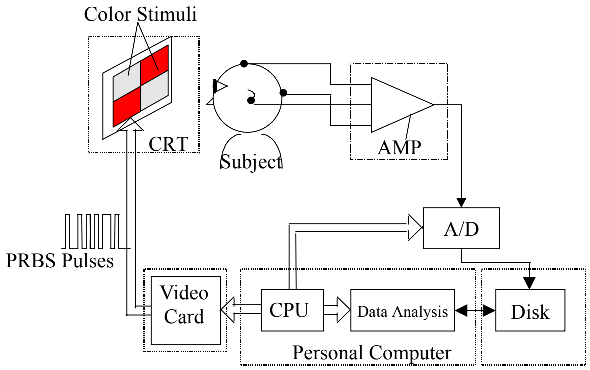


Fig.1. Color stimulation and VEP measurement systems.

that were rapidly alternated according to a PRBS. The PRBS was generated by a 12-bit shift register, and the shift register transitions were paced by a clock interval of 10 ms. This is the vertical scanning interval of the color monitor (SONY GDM-F500R) on which the color stimuli were generated. Therefore, the duration of the stimulus was 40,950 ms (=(2^{12}-1) x 10 ms). Subjects viewed the stimulus binocularly, and the stimulus subtended a horizontal and vertical visual angle of 8 x 6 degrees, respectively.

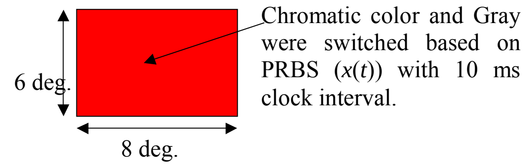
VEPs elicited by two kinds of stimuli, C1 and C2, were recorded and their binary kernels were compared. C1 was a one color stimulus with an iso-luminant color stimulus alternated with a gray stimulus presented on the full field of the color monitor (Fig. 2 (a)). C2 was a two color stimuli that was presented simultaneously with the stimulation field (monitor) divided into four squares. The two different iso-luminant color stimuli were presented in each square and each was alternated with a gray field (Fig. 2 (b)).

The iso-luminant color stimulus was rapidly alternated with the two color targets. Achromatic and chromatic colors whose luminance was constant (15 cd/m^2) were switched by PRBS to elicit the VEPs. The achromatic stimulus (gray) was fixed as illuminant C, and the following eight chromatic colors were used: B, G, Y, and R (Fig. 3). The chromatic colors were selected on the basis of cone sensitivities. The chromatic variation along the LM axis in Fig. 2 (i.e., modulation of illuminant C and R or G) modulated only the activities of the L and M cones, while variation along the S axis modulated the activity of the S cones [3].

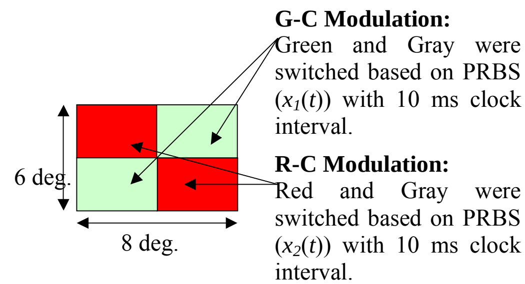
For C1, VEPs to B, G, Y and R were recorded, and for C2, one color stimulus was based on a PRBS ($x_1(t)$) and the other was based on the shifted PRBS ($x_2(t) = x_1(t-\sigma)$). VEPs to simultaneous R-G stimulation and Y-B stimulation were recorded.

C.VEP Measurement and Analysis

Bipolar EEG recordings were made between Oz and Cz (10-20 electrode system) with grounding at both ears. The amplified EEG signals were fed to an A/D converter with a sampling frequency of 500 Hz. The stimulus was repeated



(a) One color stimulus (C1).



$$x_1(t-\sigma) = x_2(t) \qquad \sigma = \frac{M+1}{2} \qquad M\text{: Length of PRBS}$$

(a) Simultaneous two color stimuli (C2).
This figure illustrates the simultaneous presentation of the R and G stimuli.

Fig. 2. Color stimulation presented on color monitor.

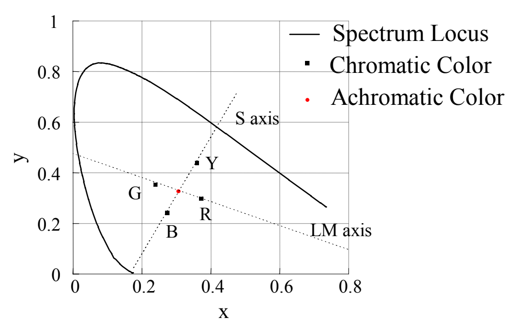


Fig. 3. Chromaticity Diagram

three times, and the responses were averaged to extract the VEPs. VEPs for each stimulus were recorded from four color-normal subjects.

Binary kernel slices were estimated by calculating the first-order cross-correlation function between the PRBS and the corresponding measured VEP.

III. Results

The first- and second-order kernel slices obtained from one subject's VEPs are sorted in Fig. 4. The two kernels obtained from VEPs to C1 and C2 are overlaid, and the waveforms of the first-order kernels depended on the color of the stimulus (Fig. 4). The second-order kernels for R and G stimulation were approximately the same, and those for B and Y were of low amplitudes. The peak-polarity of the first-order kernels from 100 to 200 ms was different for the color of the stimuli, while the implicit times of the peaks and valleys were generally equivalent. These results indicate that only the first-order binary kernels include the responses to the color stimulus that is in agreement with previous studies [4]-[6].

In comparing the results for C1 and C2 stimulation, the implicit times of the peaks and valleys of the binary kernels were approximately the same. For Y and R stimulation, the waveform of binary kernels obtained from C1 and C2 stimulation were approximately the same, although the implicit times of C2 were longer than those of C1 between 150 and 300 ms. For B and G stimulation, the amplitudes of the binary kernels for C2 were smaller than those for C1, although the implicit times of the peaks and valleys were approximately the same. As shown in each graph of Fig. 4, the correlation coefficients (r) of R and B were high, but those of G and Y were low for the first-order kernels.

IV. Discussion

The binary expansion analysis technique for a multi-input system used in this study has been used for recording multifocal ERGs and VEPs [9]-[13]. Individual responses to small stimulus patches in the visual field can be recorded by this technique and an objective measurement system for detecting small visual field defects has been developed [11] and used for clinical studies [12][13].

We have applied this technique to detect the color responses in the VEPs to multi-color stimulation. The binary kernels to each color stimulation of C2 were detected and their waveforms were similar to those obtained from C1 stimulation. This agreement indicates that multi-color stimulation (C2) can be effective for measuring the human color responses in a short time. Multi-color stimulation with two color stimuli can reduce the measurement time to approximately one-half of the conventional method. For example, only four sessions of VEP measurements, i.e. half of eight sessions, are necessary to obtain the corresponding results of the previous studies [4][5].

Previously, we demonstrated that the waveform of the first-order kernels was different depending on the color of the stimulus, and those of the second-order kernels were approximately the same except for Y and B stimuli [4][5]. This would indicate that the first-order kernels include chromatic components. We also presented evidence that the first-order kernels include the R-G and Y-B responses (opponent-color responses) [4][5], which are carried through the R-G and Y-B channels, respectively [2]. The first-order kernels correspond to the impulse responses of the linear component of the system, and the second-order kernels describe the nonlinearity of the system. The differences of the second-order kernels also indicated a difference in the nonlinearity between the two chromatic channels.

The relationship between the waveform of the binary kernels and the color of the stimuli (Fig. 4) agreed with those in previous studies. The waveform of first-order kernels is dependent on the colors of the stimuli, and the reverse of first-order kernels ($-b_1(\tau)$) for R (Y) is similar to those for G (B), indicating that the first-order binary kernels includes the opponent-color responses.

Furthermore, the results of the simultaneous presentation of two color stimuli (C2) also agreed with the previous

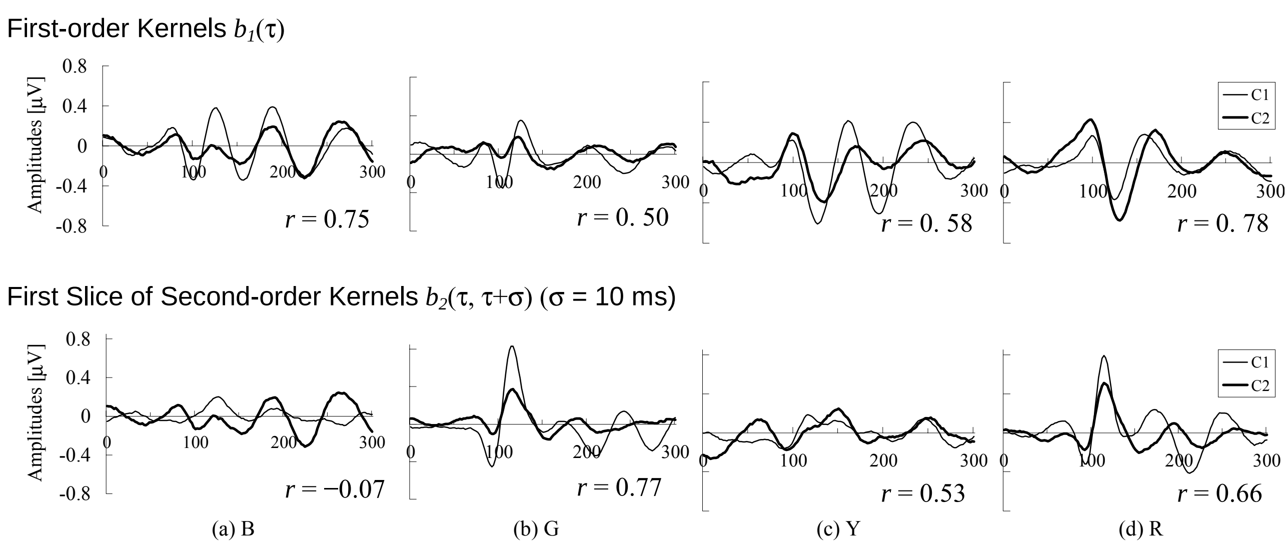


Fig. 4. Kernels obtained from one subject's VEPs elicited by (a) blue, (b) green, (c) yellow, and (d) red stimuli. Top shows first-order kernels ($b_1(\tau)$). Waveforms on second line is first slice of second-order kernel $b_2(\tau, \tau+\sigma)$ (σ = 10 ms). Two kernels obtained from C1 and C2 stimulation are overlaid. The correlation coefficients (r) between two overlaid kernels are presented for each graph.

results. This indicated that the multi-color stimulation can be used effectively to record the color responses by the VEP. A shorter measurement time can be obtained by using multi-color stimulation in which more than two color stimulation are presented simultaneously. However, in C2 stimulation, the amplitudes of binary kernels for one color were smaller than those in C1 stimulation. This may be because the effect of each color stimulus was depressed by the simultaneous presentation. A balance of the features of two colors in C2 stimulation, e.g. chromaticity and stimulus size, should be considered in future studies.

V. Conclusion

To develop a practical and rapid method to measure human color responses using visual evoked potentials (VEPs), simultaneous presentations of two iso-luminant color modulation stimuli were used. The waveform of first-order binary kernels obtained by the two color stimuli was similar to those obtained by one color stimulation indicating that simultaneous presentation of two color stimulation is effective for detecting color responses. However, in the case of some stimulus colors, the effect of each color stimulus was weakened by the simultaneous presentation.

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